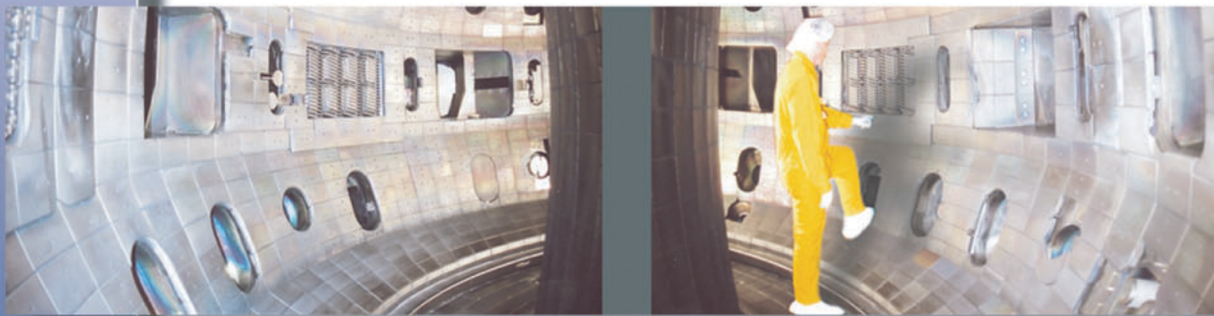
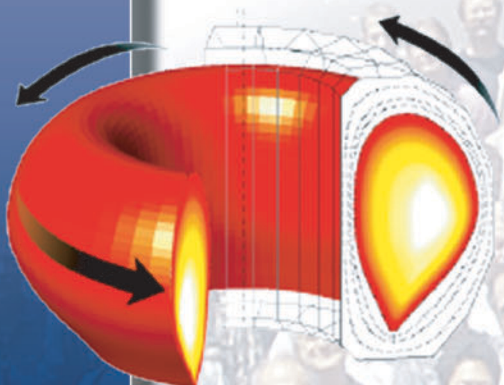
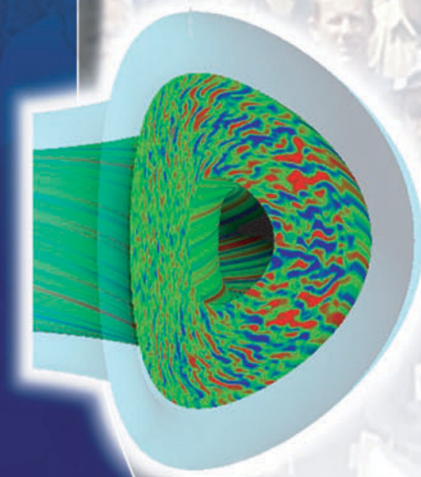






DIII–D Research Plans

by
M.R. Wade

Presented at
Office of Fusion Energy Science
FY07 Budget Planning Meeting
Washington, DC

March 15-16, 2005

015-05/AMG/jy

DIII–D
NATIONAL FUSION FACILITY
SAN DIEGO

DIII–D MISSION: TO ESTABLISH THE SCIENTIFIC BASIS FOR THE OPTIMIZATION OF THE TOKAMAK APPROACH TO FUSION ENERGY PRODUCTION

Program objectives:

- Advance the fundamental science understanding of fusion plasmas
- Enable the success of ITER by providing solutions to key issues
- Enrich the ITER physics program through development and characterization of advanced scenarios
- Develop the physics basis for high performance, steady-state operation in ITER (and beyond)

DIII–D RESEARCH PROGRAM IS AIMED AT ENSURING THE SUCCESS OF ITER WHILE ADVANCING THE SCIENCE AND INTEGRATION OF ADVANCED SCENARIOS

- DIII–D is addressing scientific issues critical to the ITER mission. Among these are:
  - Sufficient pedestal size with tolerable ELMs
  - Avoidance or stabilization of n=1 neoclassical tearing modes
  - Mitigation of disruptions
  - Tritium retention in plasma facing components
- Advanced scenario development on DIII–D suggests that an enhanced physics program should be possible on ITER
  - Advanced inductive ($Q > 40$) $\Rightarrow$ high Q burning plasma physics
  - Hybrid ($Q \sim 10$ for >1 hr) $\Rightarrow$ materials testing
  - Fully noninductive ($Q \sim 5$) $\Rightarrow$ steady-state operation
- Key to the development of these solutions and scenarios is a fundamental understanding of the basic processes that have the largest impact
  - Electron thermal transport
  - Energy and particle flow patterns in the edge
  - Alfvén eigenmode instabilities

THE VERSATILITY OF THE DIII–D FACILITY PROVIDES AN IDEAL PLATFORM FOR ADDRESSING A WIDE RANGE OF KEY FUSION SCIENCE ISSUES

- **Machine flexibility**
  - Plasma shaping
  - Co-, counter-, and balanced NBI
  - Complementary set of heating and current drive systems
  - Density control in a variety of plasma configurations
  - Non-axisymmetric coil set

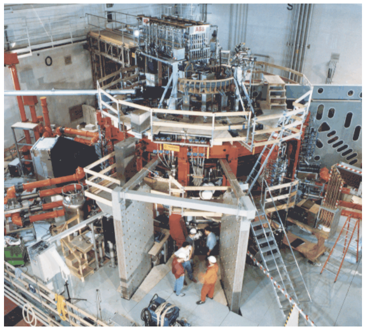
- **Diagnostics**
  - Full suite of profile diagnostics (core, edge, and divertor)
  - Expanding set of fluctuation diagnostics (core and edge)
  - Complementary set of analysis codes

- **Operating scenarios**
  - Fully noninductive, β_N ~ 4 (Advanced Tokamak)
  - Stationary, high performance (hybrid and advanced inductive)
  - Conventional H–mode (ITER baseline scenario)
  - Other: QH–mode, QDB, VH–mode, High ℓ_i, L–mode, . . .

- **International research team**

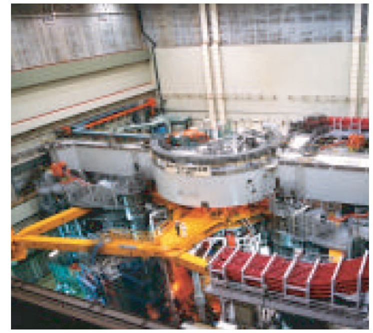
DIII–D VERSATILITY PROMOTES COMPARATIVE STUDIES WITH FUSION FACILITIES WORLDWIDE

ASDEX



— Hybrid
— QH-mode
— Pedestal
— Modulated transport
— NTM

JT-60U

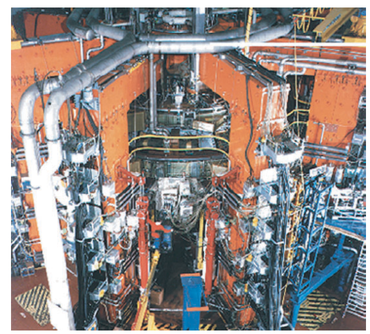


— Advanced Tokamak
— Hybrid
— QH-mode
— Current hole

Alcator C-Mod

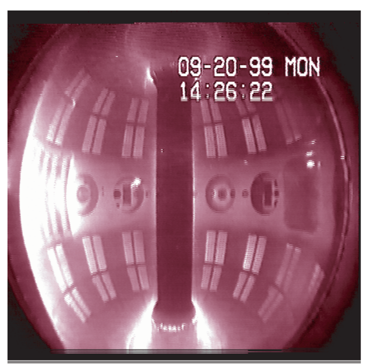
— Pedestal
— Momentum transport
— Edge/divertor

JET



— Transport
— RWM
— Current hole
— QH-mode
— Hybrid
— NTM

NSTX



— Fast ion instabilities
— Pedestal
— Transport
— Plasma control
— RWM

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SCIENTIFIC PERSONNEL EXCHANGES ENHANCE COLLABORATIONS AND JOINT EXPERIMENTS

2004 -2005

to DIII–D

Current hole experiments
E. Solano (CIEMAT) N. Hawkes (UKAEA)

Critical T_e gradient
F. Ryter, A. Manni (MPI)

RWM stabilization
M. Takechi (JAERI) S. Pinches (MPI)
R. Buttery (UKAEA)

NTM stabilization
R. Buttery (UKAEA) O. Sauter (CRPP)
A. Isayama (JAERI) M. Maraschek (MPI)

Beta scaling of confinement
D. McDonald (UKAEA)

Hybrid scenarios
A.C.C. Sips E. Joffrin (CEA-Cadarache)

EHO identification and QH–mode
F. Nave (JET) H. Urano (JAERI)
Y. Sakamoto (JAERI)

Disruption mitigation
D. Howell (UKAEA)

Edge stochastization
P. Thomas, M. Becoulet, P. Monier-Garbet (CEA-Cadarache)
E. Nardon, F. Dubois (CEA-Cadarache)
J. Harris (ANU, Australia)
K-H. Finken, M. Lehmen (TEXTOR)
N. Nishino (Hiroshima Univ.)

Error field effects
D. Howell (UKAEA)

Current profile measurement control
R. Giannella (CEA-Cadarache) D. Mazon (JET)

from DIII–D

Thomson scattering at JET
T. Carlstrom
B. Bray

Remote participation in QH–mode (JT–60U)
L. Lao
P. Gohil
P. West

RWM at JET
R. La Haye, H. Reimerdes

AT and hybrid scenario JT–60U
M. Wade
T. Luce
M. Murakami

Confinement studies (ANU)
T. Luce

Hybrid scenarios (ASDEX Upgrade)
M. Wade

Boundary physics (ASDEX Upgrade)
M. Groth

Error field harmonics (JET)
T. Scoville

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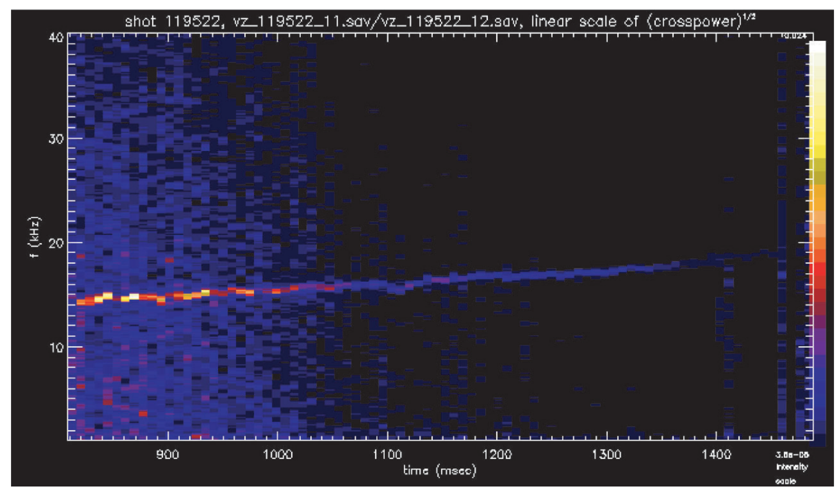
DIII–D HAD A SUCCESSFUL YEAR: RESEARCH HIGHLIGHTS IN 2004

- Feedback stabilization of the RWM achieved in low rotation plasmas using internal control coils
- First demonstration of resistive wall mode stabilization with new high-bandwidth (audio) amplifiers
- Pre-emptive electron cyclotron current drive avoids neoclassical tearing modes, allowing higher beta
- Active feedback control of the q-profile, using real-time equilibrium reconstruction with motional Stark effect data
- Modulated heating experiments find no evidence of a critical temperature gradient in electron thermal transport.
- Comprehensive set of turbulence diagnostics covers the full range of transport-relevant wavenumbers (0–40 cm^{-1})

Geodesic Acoustic Mode Observed in Turbulent $\tilde{v}_\theta$ Field (Upgrade BES)



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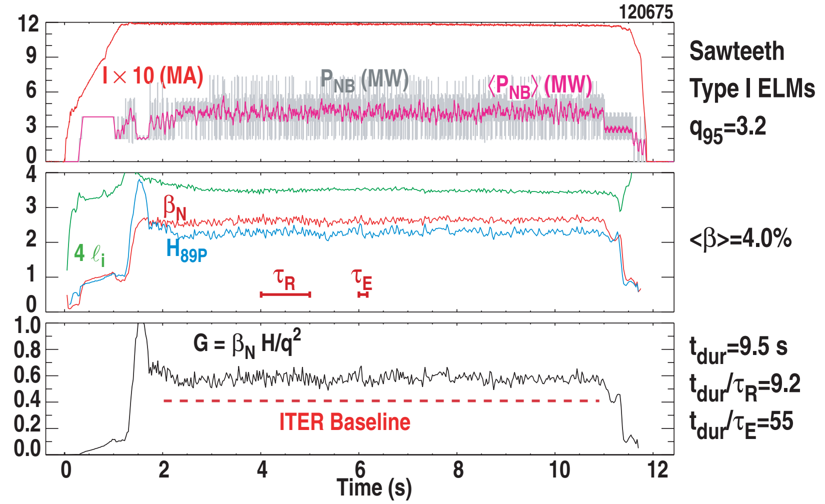
RESEARCH HIGHLIGHTS IN 2004 (Continued)

- Used localized current drive to show that the m/n = 3/2 tearing mode regulates central current profile in "hybrid" plasmas.
- Core localized "Sea of Alfvén Eigenmodes" identified in weakly reversed shear plasmas with ITER-relevant conditions
- ELMs suppressed in plasmas with ITER shape and aspect ratio, using n=3 resonant magnetic perturbations.
- m/n = 3/2 neoclassical tearing mode onset β shown to scale with ρ_i^*, implying instability for ITER baseline scenario.
- 100% noninductively driven plasmas with good current drive alignment and $\beta_N \leq 3.5$, for up to one current relaxation time
- Carbon 13 migration experiments show poloidal flow of hydrocarbons and deposition near the inner strike point
- Edge profile measurements show that QH–mode plasmas lie at the current driven limit for peeling/ballooning modes
- Stationary ($t_{dur} > 9\ \tau_R$) high performance discharges achieved that scale favorably to ITER



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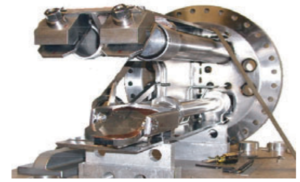
DIII–D NATIONAL FUSION FACILITY SAN DIEGO

KEY PLASMA CONTROL TOOLS WILL BE AVAILABLE IN FY06

Key Hardware Element	Physics/Control

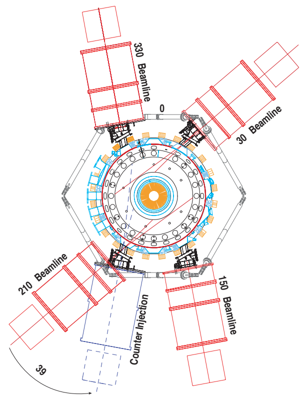
Long-pulse EC systems

	Present		Plan
LP	3	$\Rightarrow$	6 $\Rightarrow$ 8
SP	3	$\Rightarrow$	0

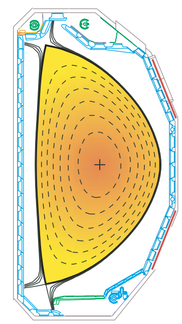
- J(ρ) control
- P(ρ), transport studies
- NTM stabilization

Counter NBI



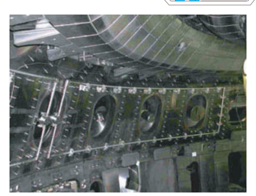
- Transport
- RWM (low rotation)
- Fast ion physics
- MSE for E_r

High δ divertor



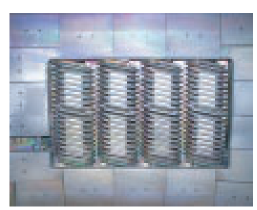
- n_e control in DND and SND, ITER δ
- Pedestal physics over range of ν^*

Internal coil
- High bandwidth actuators first phase completed



- RWM feedback
- Stochastic edge

FW system operation
- ABB $\Rightarrow$ EIMAC tube



- J (ρ~0) and P(ρ) control
- $\beta_e \uparrow$ for improved current drive efficiency

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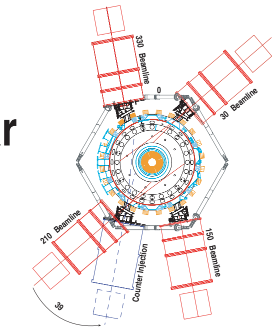
TRANSPORT AND CONFINEMENT: NEW TOOLS AND DIAGNOSTICS AVAILABLE IN FY2006



- Co plus counter neutral beam injection (balanced up to 10 MW)
  - Allows direct control of toroidal rotation, radial electric field and E×B shear

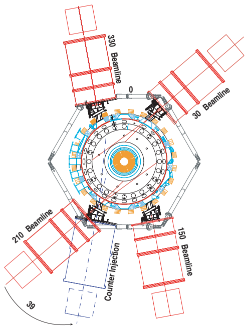
- Longer pulse, higher power EC system allows T_e and j-profile control for transport studies
- New computer cluster
  - Will allow much better throughput for computationally intensive codes such as GYRO
  - Essential for effective theory-experiment comparison of turbulence results

- Improved turbulence diagnostics
  - Turbulent density field ($0.1 \lesssim k_\perp \rho_s \lesssim 10$)
  - Turbulent velocity field ($0.1 \lesssim k_\perp \rho_s \lesssim 0.3$)
- Improved turbulence analysis techniques
  - Energy flows in k-space from BES two-field measurements
  - Local turbulent particle transport measurements in core and edge

DIII–D TRANSPORT AND CONFINEMENT PHYSICS PLAN FOR FY 06–07

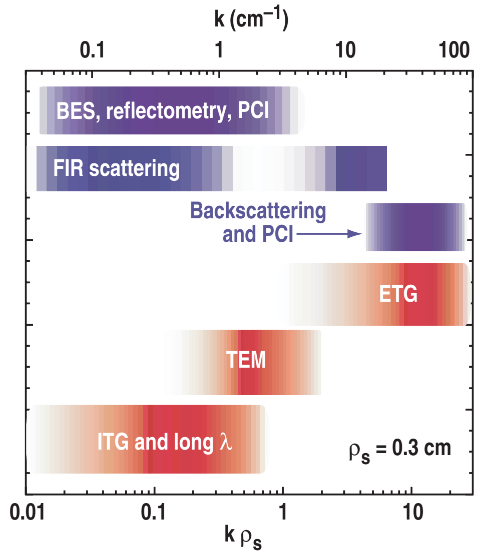
- Turbulence characterization
  - Characterize turbulence over a wide range of spatial scales and compare with gyrokinetic code (GYRO) predictions
  - Zonal flow studies using upgraded BES
- Electron thermal transport
  - Investigate link between short wavelength turbulence and electron transport
  - Study critical gradient effects using modulated ECH

- Transport barriers
  - Explore link between E×B shear and long wavelength turbulence
  - Differentiate between Shafranov shift and E×B effects on barrier formation
- Momentum transport
  - Separate heat and angular momentum input
  - Determine mechanism that allows rotation without momentum input

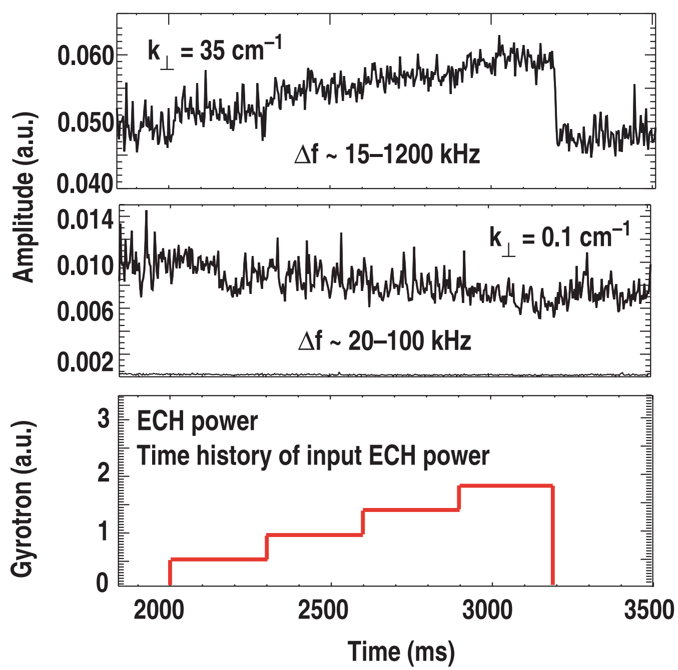


TOOLS ARE NOW IN PLACE FOR A CONCERTED EFFORT ON CHARACTERIZING TRANSPORT AT ALL SPATIAL SCALES

- Turbulence diagnostics now cover all relevant spatial scales

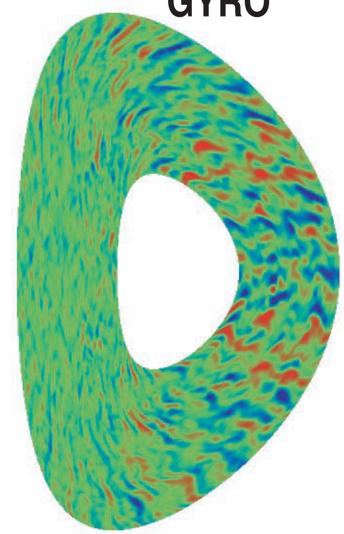


- Allows simultaneous measurement of fluctuations at different scale lengths ...



- ... and comparison with theory

GYRO



Fusion Microturbulence Simulation Initiative

Diagnostics:

— FIR, reflectometer, microwave backscattering (UCLA)

— BES (U. Wisconsin)

— Phase constrast imaging (MIT)

- TTF initiative

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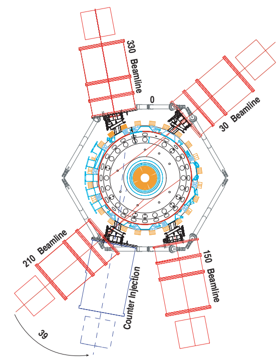
DIII–D STABILITY PHYSICS RESOURCES AND PLAN ELEMENTS

- **Resources**
  - Non-axisymmetric coils
  - Fast ion profile diagnostic (proposed)
  - Co-, counter-, and balanced NBI
  - Long-pulse ECCD
  - Fast camera for disruption studies
  - Fast ion mode diagnostics



- **Plan**
  - Characterize fast particle physics
    - ★ Measure fast ion distribution
    - ★ Alfvén eigenmodes: characterize and validate models
  - Nonlinear MHD
    - ★ Develop physics understanding of sawteeth, interchange, and resistive MHD
    - ★ Study 3D equilibrium effects
  - Disruption mitigation and characterization
  - NTM stabilization
  - RWM stabilization at low rotation

} in ITER/AT section

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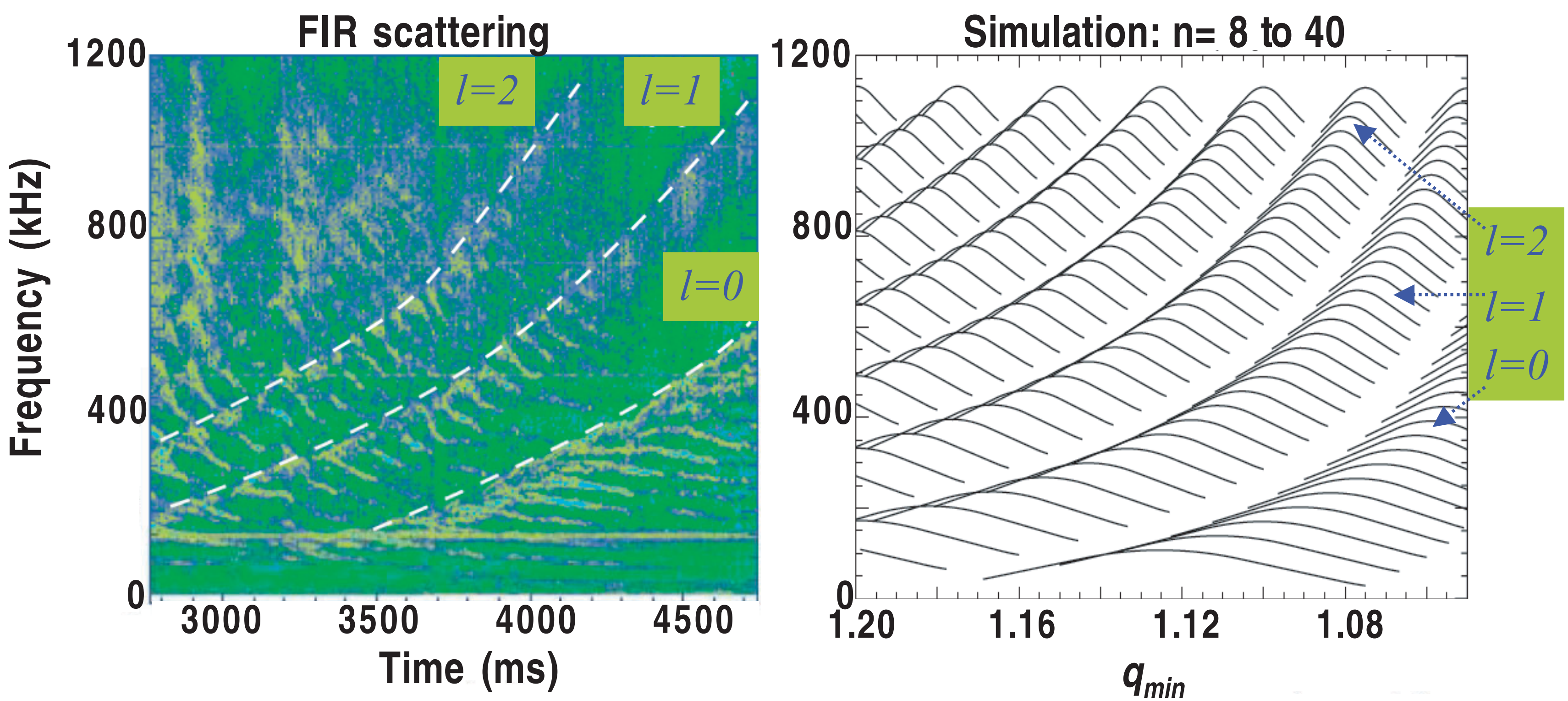
NEW DIAGNOSTICS ALLOW DETAILED STUDIES OF FAST ION DRIVEN INSTABILITIES



- **Contributing diagnostics:**
  - FIR scattering, CO_2 interferometer, BES, reflectometer, phase contrast imaging, rf loop
- **Proposed**
  - D_α fast ion profile (UC Irvine, PhD thesis)
  - Expanded BES

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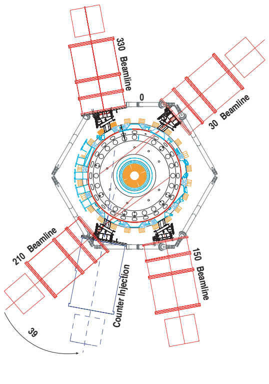
DIII–D HEATING AND CURRENT DRIVE PHYSICS PLAN FOR FY06-07

- **Resources**
  - Long pulse ECCD with increased power
  - Co-, counter-, and balanced NBI
  - Improved FW system
  - Improved q profile and E_r measurement (MSE upgrade)
  - Fast ion profile measurement



- **Plan**
  - FWCD
    - ★ Test models of fast ion damping, electron absorption, and current drive
    - ★ Apply to Advanced Tokamak plasmas
  - ECCD
    - ★ Continue to validate linear and quasi-linear codes
  - Bootstrap current
    - ★ Develop $f_{BS} \approx 1$ plasmas with balanced NBI
  - NBCD
    - ★ Test models using co-, counter-, and balanced NBI capability

RESTART OF THE DIII–D FAST WAVE SYSTEM HAS PROGRESSED WELL WITH 2.7 MW COUPLED TO AN L-MODE PLASMA

— Collaborative effort of GA, ORNL, and PPPL —

	0°	180°	285°
f (MHz)	118	115	60
P_{FW} (MW)	0.87	0.97	1.18
$P_{coupled}$ (MW)	0.76	0.84	1.11

- Total FW power = 3.0 MW
- Total coupled power = 2.7 MW
- Transmitter-limited
- Operated in both co- and counter-current phasings (milestone)

- GA: Operations support
- ORNL: Transmission line and antennae
- PPPL: Power systems and transmitters

- Initial studies indicate less parasitic absorption by beam ions at 117 MHz than 60 MHz
  - Not expected from code predictions
    - ★ Good news for FWCD in AT plasmas

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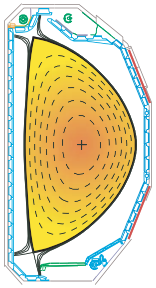
DIII–D BOUNDARY PHYSICS PLAN FOR FY06-07

- **Resources**
  - SN and DN pumped divertor at ITER-like triangularity
  - Allows operation over wide range in pedestal collisionality ($0.01 < \nu_* < 3$)
  - Improved diagnostic set: Quartz microbalance, probes, cameras
  - Codes: UEDGE, BOUT, kinetic BOUT, DIVIMP, OEDGE, DEGAS-2



- **Plan**
  - Power and particle control
    - ★ Understand particle control for SND $\rightarrow$ DND over range of edge collisionality
    - ★ Explore radiative divertor solutions for high performance scenarios
  - SOL dynamics
    - ★ Test BOUT simulations of radial transport in SOL
    - ★ Characterize heat and particle flow during ELMs, validate models
    - ★ Divertor and SOL response in ELM suppressed regimes
  - Understand flow of particles in SOL/divertor
    - ★ Parallel flow, cross-field diffusion, and drifts
    - ★ Carbon migration and co-deposition

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DIII–D RESEARCH PROGRAM WILL CONTINUE TO PROVIDE TIMELY INFORMATION ON KEY ISSUES OF ITER DESIGN AND OPERATION

- Enable the success of ITER by providing solutions to key issues
  - H-mode pedestal understanding and control
    - ★ Physics determining pedestal height
    - ★ ELM mitigation: QH-mode, stochastic edge
  - NTM stabilization
  - Physics of impurity and tritium mass transport
  - Disruption characterization and mitigation
  - Develop core transport models to validate performance projection and guide operation
  - Fast ion physics and fast-ion driven instabilities
  - Reduction of heat flux to the divertor
  - Diagnostic development
- Enrich the ITER physics program through development and characterization of advanced scenarios
  - Develop long pulse, high performance discharges for ITER
  - RWM stabilization
  - Validate models of ECCD and FWCD

DIII–D RESEARCHERS ARE STRONGLY ENGAGED IN INTERNATIONAL TOKAMAK PHYSICS ACTIVITY (ITPA)

— 35 team members, 3 international chairs/co-chairs, 8 US leaders/co-leaders —

Coordination Committee	Oktay
Erol Oktay	OFES
Ned Sauthoff	PPPL
Ron Stambaugh	GA

Transport Physics (TP)	Bolton
Ed Doyle	UCLA
Ed Synakowski	PPPL
John Rice	MIT
John Kinsey	Lehigh
Punit Gohil	GA
Dave Mikkelsen-Stell.	PPPL
Michael Kotschenreuther	Texas
Catherine Fiore	MIT
Larry Baylor	ORNL
Wendell Horton	Texas
Chuck Greenfield	GA
T.S. Hahm	PPPL
Bill Nevins	LLNL
Martin Peng	PPPL/ORNL
Ron Waltz	GA
Jim Callen	PPPL/ORNL

Pedestal & Edge Physics (PEP)	
Tony Leonard	GA
Amanda Hubbard	MIT
Parvez Guzdar	Maryland
Tom Rognlien	LLNL
Mickey Wade	ORNL
Xueqaqio Xu	LLNL
Phil Snyder	GA
Rich Groebner	GA
Rip Perkins	PPPL
Tom Osborne	GA
Jim Drake	Maryland
Ben Leblanc	PPPL

Steady State Opseartions (SSO)	Oktay
Tim Luce	GA
Paul Bonoli	MIT
Ron Prater	GA
Chuck Kessel	PPPL
Masanori Murakami	ORNL
Randy Wilson	PPPL
Mike Zarnstorff	PPPL
Pete Politzer	GA
Joel Hosea	ORNL
Cary Forest	Wisconsin U

MHD, Disruption and Control (MDC)	Dagazian
Ted Strait	GA
William Heibrink	UCI
Robert Granetz	MIT
Jon Menard	PPPL
Gerry Navratil	Columbia
Ed Lazarus-Stellarator	ORNL
Chris Hegna	Wisconsin
Eric Fredrickson	PPPL
John Wesley	GA
Steve Jardin	PPPL
Boris Breizman	Texas
Raffi Nazikian	PPPL
Doug Darrow	PPPL
Nicolai Gorelenko	PPPL
Steve Sabbagh	Columbia

Confinement, Database, and Modeling (CDBM)	Eckstrand
Wayne Houlberg	ORNL
Jim DeBoo	GA
Stan Kaye	PPPL
Joe Snipes	MIT
Robert Budny	PPPL
Tom Casper	LLNL
Craig Petty	GA
Lynda Lodestro	LLNL
Glenn Bateman	Lehigh
Dale Meade	PPPL
Arnold Kritz	Lehigh
Martin Greenwald	MIT

Divertor Physics & Scrape-off-layer (DSOL)	Finfgeld
Bruce Lipschultz	MIT
Peter Stangeby	LLNL/GA
Dennis Whyte	Wisconsin
Sergei Krasheninnikov	UCSD
Max Fenstermacher	LLNL
Rajesh Maingi	ORNL
Ali Mahdavi	GA
Daren Stotler	PPPL
John Hogan	ORNL
Gary Porter	LLNL
Charles Skinner	PPPL
Henry Kugel	PPPL
Jim Strachan	
Mathias Groth	LLNL
Steve Lisgo	U Toronto

Diagnostics	Markevich
Dave Johnson	PPPL
Rejean Boivin	GA
Tony Peebles	UCLA
George McKee	Wisconsin
Glenn Wurden	LANL
Don Hillis	ORNL
Ray Fisher	GA
Ken Young	PPPL
Jim Terry	MIT

Notes:
1. The first five persons in each group are the core members
2. The first person in each group is the U.S. Leader
3. The second person is the U.S. deputy leader
4. The membership is open to all members of the U.S. community
5. Everyone on the list will receive communication on ITPA and be able to contribute to it.

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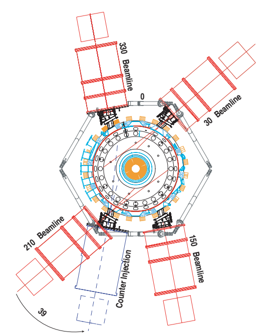
015–05/TST/wj

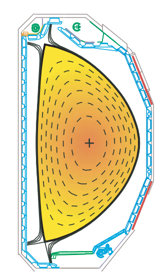
UNDERSTANDING AND CONTROLLING THE H-MODE PEDESTAL IS A PRIMARY FOCUS OF THE DIII–D PROGRAM

- **Develop predictive understanding**
  - Test stability predictions (linear and nonlinear – ELITE, BOUT, NIMROD)
  - Develop and test transport theories (GLF23, kinetic BOUT, NIMROD)
  - Make comprehensive pedestal turbulence measurements

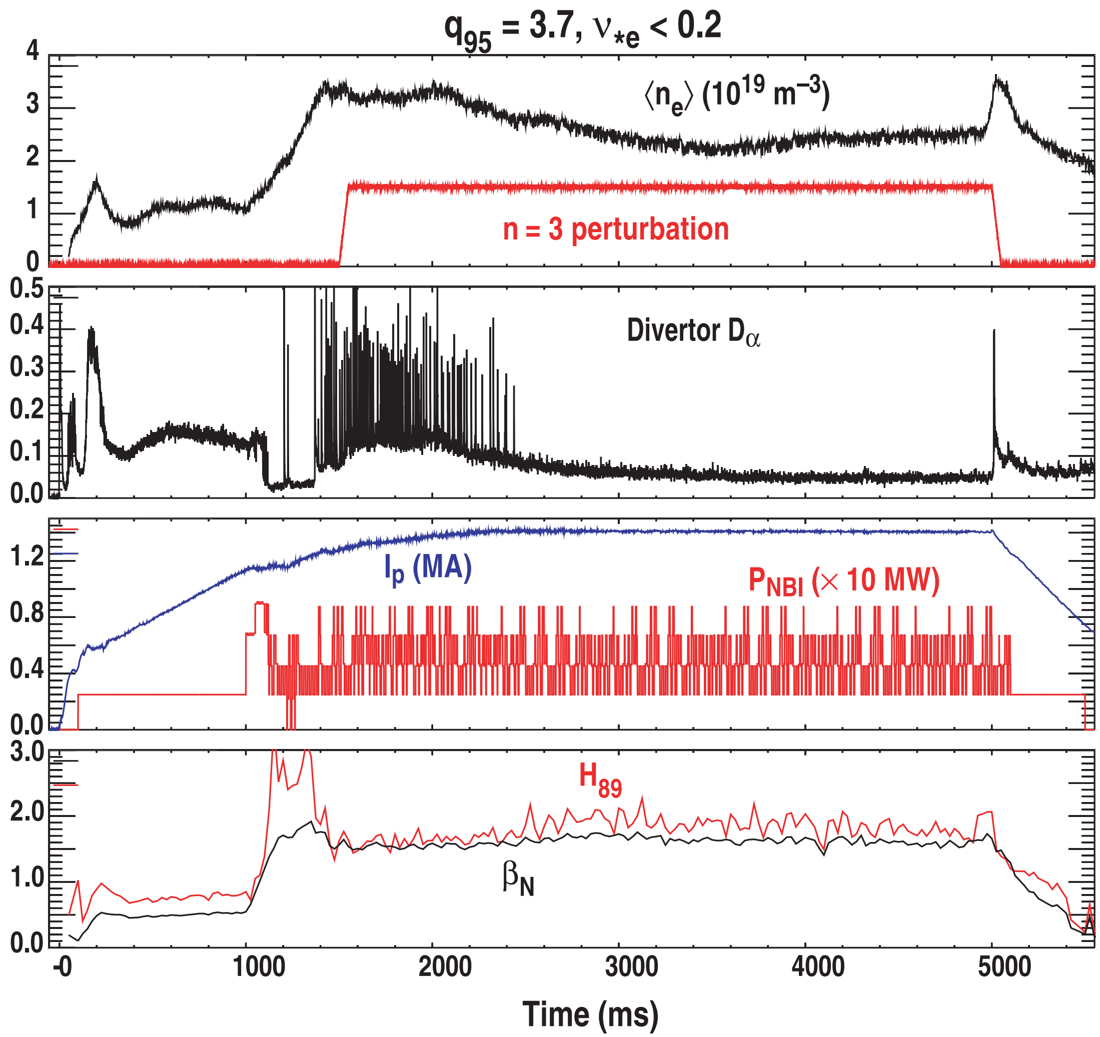
- **Develop method for controlling ELMs**
  - Utilize stochastic edge to suppress ELMs
  - Develop and characterize ELM-free regimes with good confinement (QH or VH-modes)

- **Resources**
  - Counter NBI
  - High δ pumping
  - BES upgrade, Li beam, expanded MSE
  - Fast framing camera
  - Non-axisymmetic coils

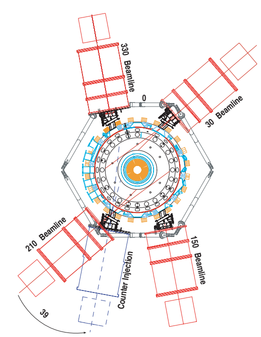




ELMs SUPPRESSED FOR MORE THAN 2.5 s AT ITER RELEVANT COLLISIONALITY USING n=3 MAGNETIC PERTURBATION



- Clear evidence for particle transport induced by n=3 perturbation
- H–mode pedestal maintained with $H_{89P} \approx 2$
- Beamline reversal will allow study of connection with QH-mode



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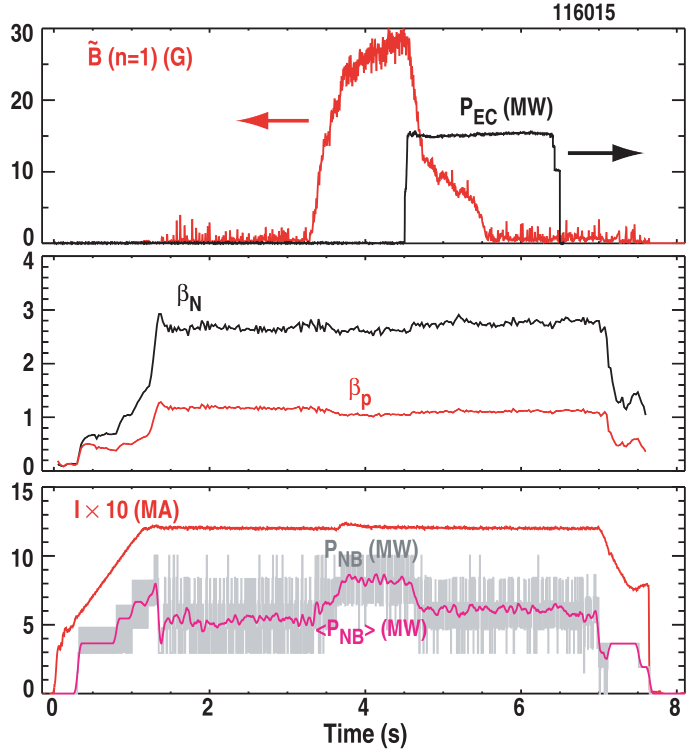
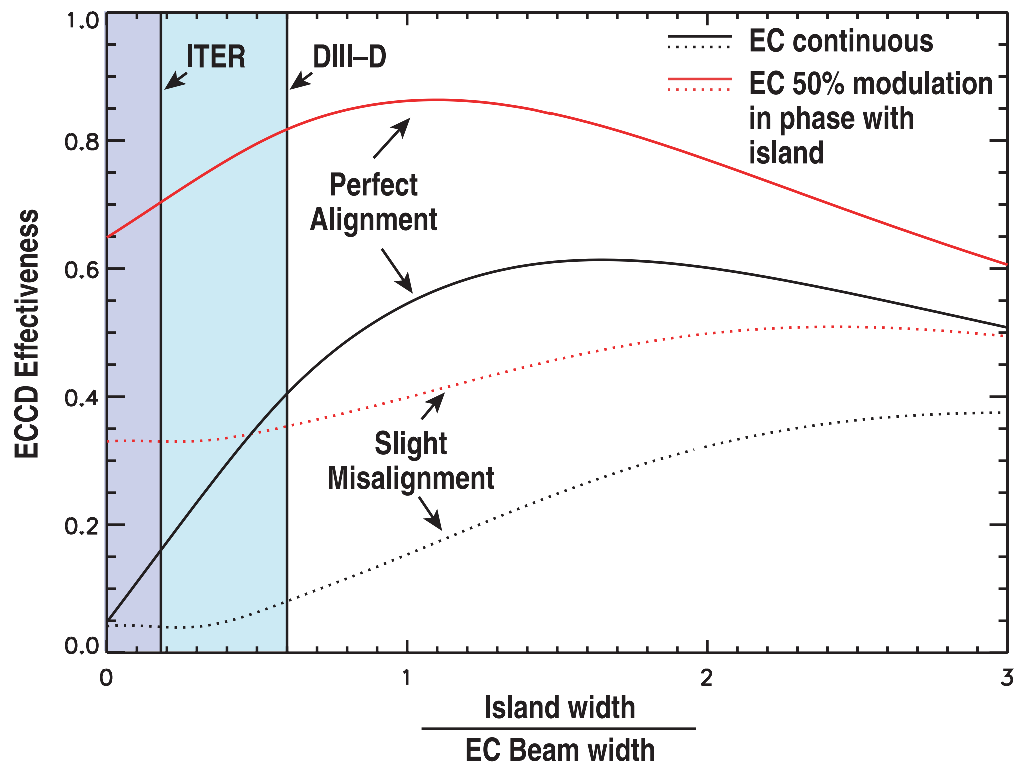
NTM STABILIZATION HAS BEEN DEMONSTRATED - MAIN ISSUE NOW IS THE POWER REQUIRED FOR STABILIZATION IN ITER

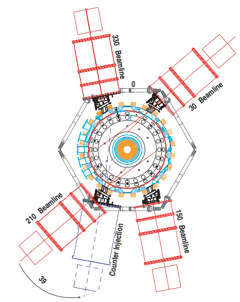
- DIII–D experiments and others have shown that ECCD can be used to stabilize 3/2 and 2/1 NTMS



- . . . but, effectiveness is limited due to continuous current drive



- Beamline rotation allows operation with sufficiently low rotation frequency for testing of ECCD modulation (< 5kHz)
- Steerable launchers (PPPL) will allow testing of alignment requirements



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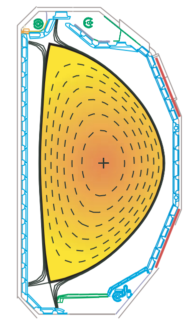
DIII–D HAS AN EXTENSIVE SET OF TOOLS FOR STUDYING CARBON MIGRATION AND TRITIUM RETENTION

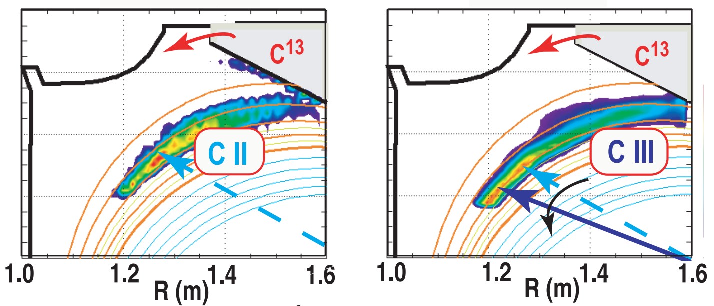
- **Resources**
  - DiMES, porous plug injector
  - Toroidally symmetric gas injection
  - Quartz microbalance detectors
  - Fast framing cameras to measure initial flow pattern
  - Off-site nuclear surface analysis by collaborators

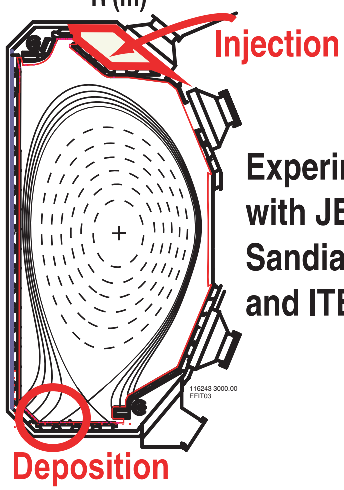


- **Plan**
  - Study erosion/deposition issues via DiMES (reconfigured for new divertor)
  - Midplane material exposive system will be added
  - Investigate carbon migration through detailed characterization and modeling of $^{13}CH_4$ injection experiments
  - Off-site oxygen bake to determine ability to recover hydrogen isotopes

EXPERIMENTS INIDICATE PREFERENTIAL DEPOSITION OF ^{13}C AT INNER DIVERTOR; NEW DIVERTOR CONFIGURATION ALLOWS DIRECT ACCESS TO THIS REGION

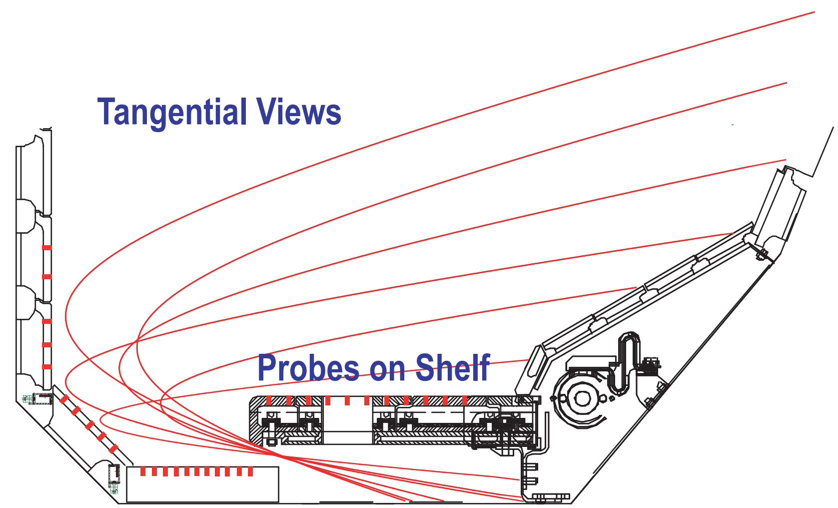
Tangential Camera Measurements (LLNL)



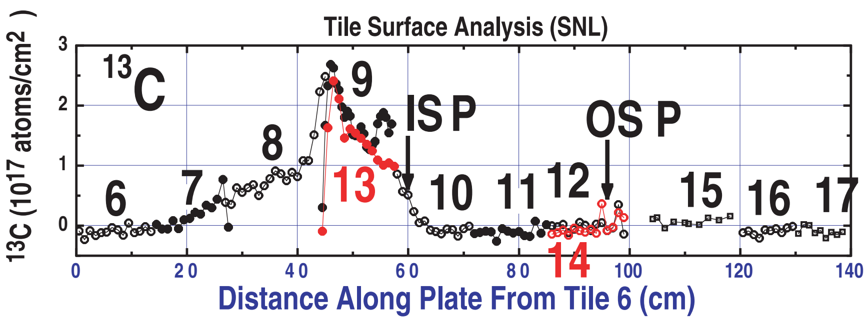


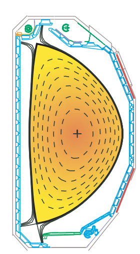
Experiment (collaboration with JET, TEXTOR, U. Wisc., Sandia, U. Toronto, and ITER Central Team)

- Measurements indicate flow of ^{13}C from injection location to inner divertor leg
- Modeling suggests M ~ 0.5 in SOL



Tile Surface Analysis (SNL)





- New divertor allows direct access to inner divertor
  - Quartz microbalance detectors
  - Spectroscopic views from under baffle

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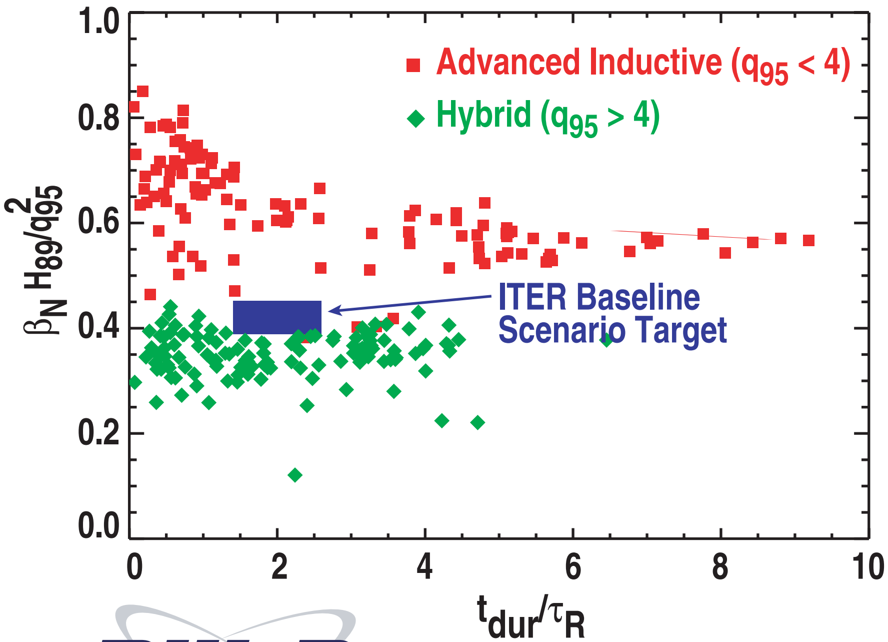
DIII–D RESEARCH PROGRAM WILL CONTINUE TO PROVIDE TIMELY INFORMATION ON KEY ISSUES OF ITER DESIGN AND OPERATION

- Enable the success of ITER by providing solutions to key issues
  - H-mode pedestal understanding and control
    - ★ Physics determining pedestal height
    - ★ ELM mitigation: QH-mode, stochastic edge
  - NTM stabilization
  - Physics of impurity and tritium mass transport
  - Disruption characterization and mitigation
  - Develop core transport models to validate performance projection and guide operation
  - Fast ion physics and fast-ion driven instabilities
  - Reduction of heat flux to the divertor
  - Diagnostic development
- Enrich the ITER physics program through development and characterization of advanced scenarios
  - Develop long pulse, high performance discharges for ITER
  - RWM stabilization
  - Validate models of ECCD and FWCD

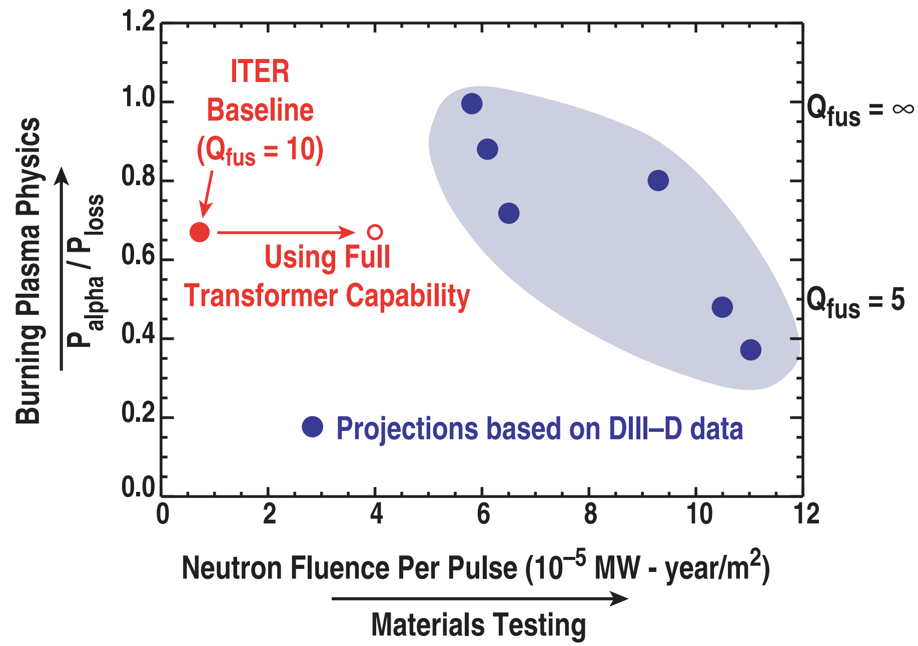
ADVANCED INDUCTIVE AND HYBRID SCENARIOS DEVELOPED ON DIII–D OFFER THE POTENTIAL OF A SIGNIFICANTLY ENHANCED RESEARCH PROGRAM ON ITER

- Advanced inductive: $q_{95} = 3.2$, $\beta_N = 2.8$, $H_{98ys} = 1.5$
  - Potential for ignition sustained for >30 minutes
- Hybrid: $q_{95} = 4.4$, $\beta_N = 2.7$, $H_{98ys} = 1.6$
  - Maximum neutron fluence ($Q \approx 10$ for >1 hour)

- Performance at or above ITER baseline maintained in stationary conditions



- Projections of DIII-D data suggests expanded research opportunites in ITER



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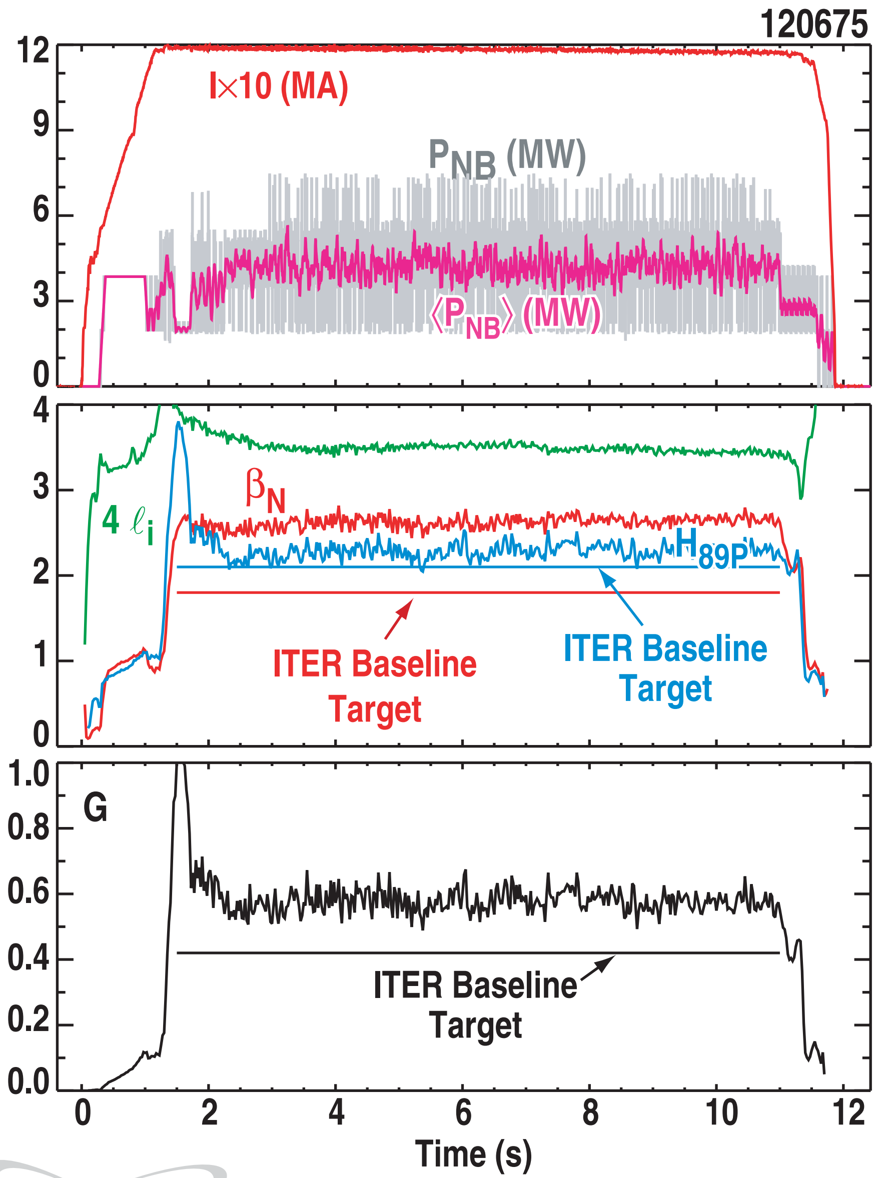
PROJECTIONS OF ADVANCED INDUCTIVE SCENARIO INDICATE FUSION POWER ENHANCEMENT AND IGNITION ARE POSSIBLE



Projection to ITER

$\beta_N = 2.8$ $q_{95} = 3.2$ $n/n_G = 0.85$

$B = 5.3$ T $I = 13.9$ MA

	H	P_{fus} (MW)	P_{aux} (MW)	Q_{fus}
ITER89P	2.4	780	60	12.9
IPB98y2	1.47	740	18.5	39
DS03	1.25 (1.63)*	700	0	∞

*DIII–D Value

Flattop time = 2300 s > 30 min

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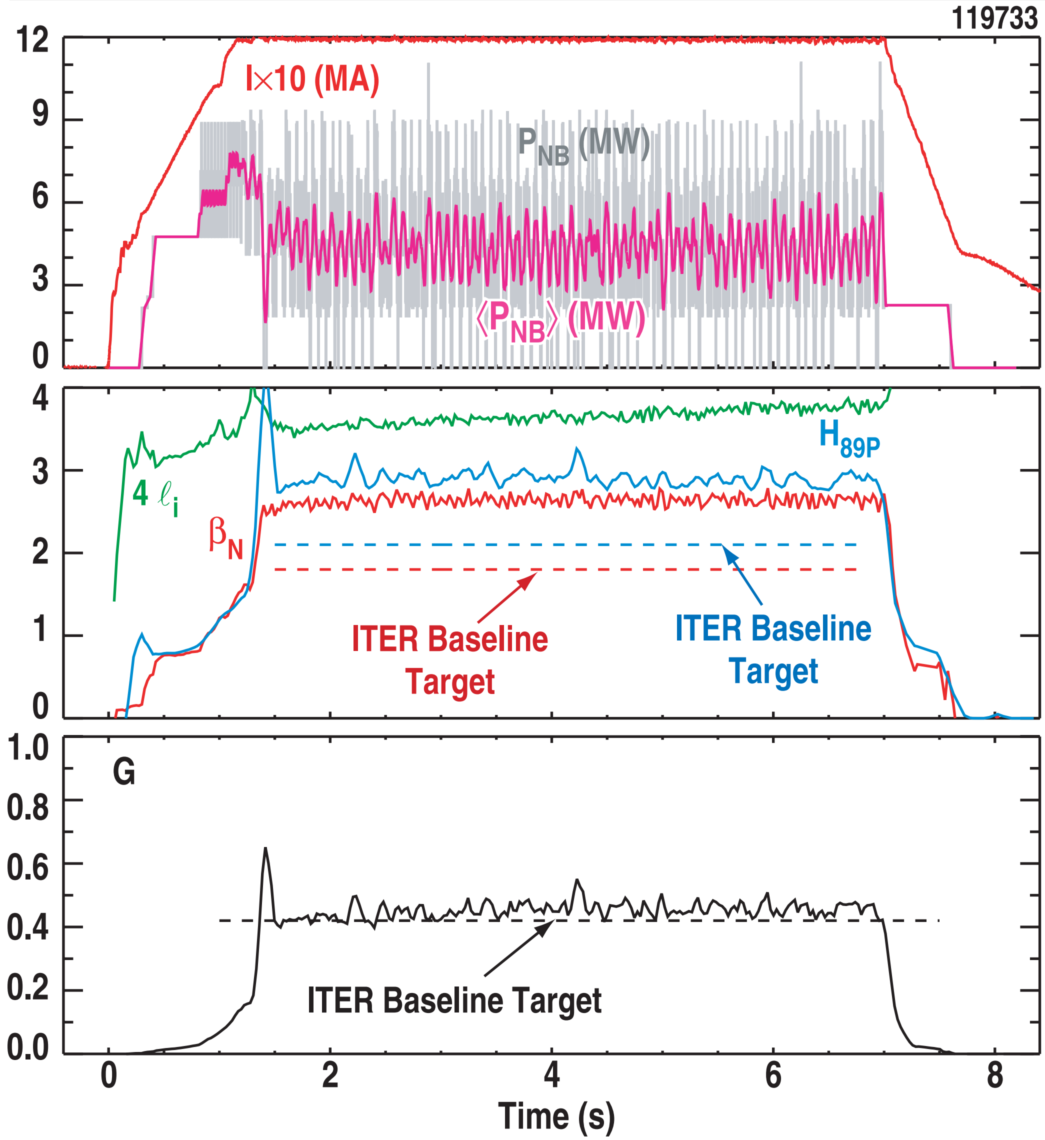
PROJECTION OF HYBRID SCENARIO INDICATE POSSIBILITY OF Q = 10 SUSTAINED FOR >1 HOUR



Projection to ITER

$\beta_N = 2.7$ $q_{95} = 4.4$ $n/n_G = 0.85$

$B = 5.3$ T $I = 10.8$ MA

	H	P_{fus} (MW)	P_{aux} (MW)	Q_{fus}
ITER89P	2.75	440	49	9.0
IPB98y2	1.59	440	49	9.0
DS03	1.78 (1.81)*	370	0	∞

*DIII–D actual value

Flattop Time = 3900 s > 1 hour

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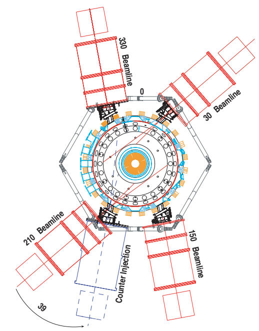
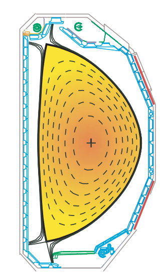
HYBRID SCENARIO RESEARCH ACTIVITIES WILL FOCUS ON KEY PHYSICS ISSUES FOR EXTRAPOLATION TO ITER

- **Energy transport**
  - Non-dimensional scaling studies
  - $T_e = T_i$
  - Low rotation
  - Turbulence characterization



- **Current transport**
  - Identify mechanism for $q_0 > 1$ in stationary conditions
    - ★ MHD-induced flux transport
    - ★ Fast ion transport
  - Develop methodology for extrapolating mechanism to ITER

- **Boundary**
  - Develop a compatible edge/divertor solution
    - ★ Stochastic edge
    - ★ Radiative divertor

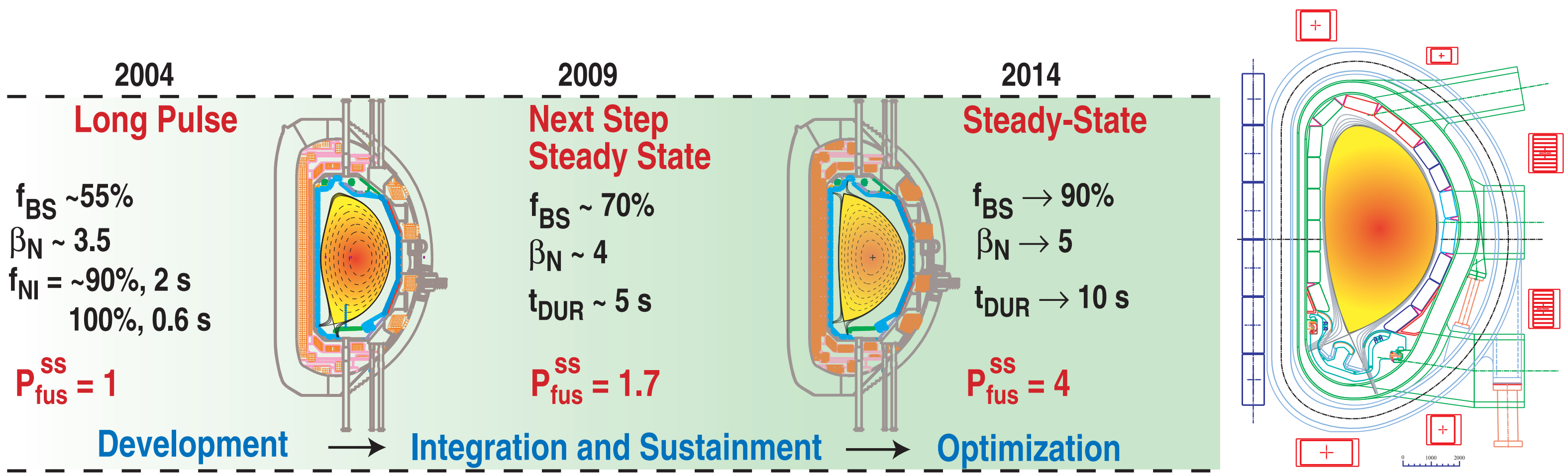


DIII–D MISSION: TO ESTABLISH THE SCIENTIFIC BASIS FOR THE OPTIMIZATION OF THE TOKAMAK APPROACH TO FUSION ENERGY PRODUCTION

Program objectives:

- Advance the fundamental science understanding of fusion plasmas
- Enable the success of ITER by providing solutions to key issues
- Enrich the ITER physics program through development and characterization of advanced scenarios
- Develop the physics basis for high performance, steady-state operation in ITER (and beyond)

THE FOCUS OF THE DIII–D PROGRAM IS THE ADVANCED TOKAMAK — REALIZING THE ULTIMATE POTENTIAL OF THE TOKAMAK



Application to ITER and beyond

Measures of progress

- Increase projected fusion power by factor of 4
  - Beyond already achieved normalized conditions equivalent to ITER steady-state scenario
- Increase advanced tokamak duration by up to a factor of 5
- Reduce driven current by factor of 4
- Approach fully bootstrap driven conditions
  - $J(\rho)$ control $\rightarrow$ $P(\rho)$ control

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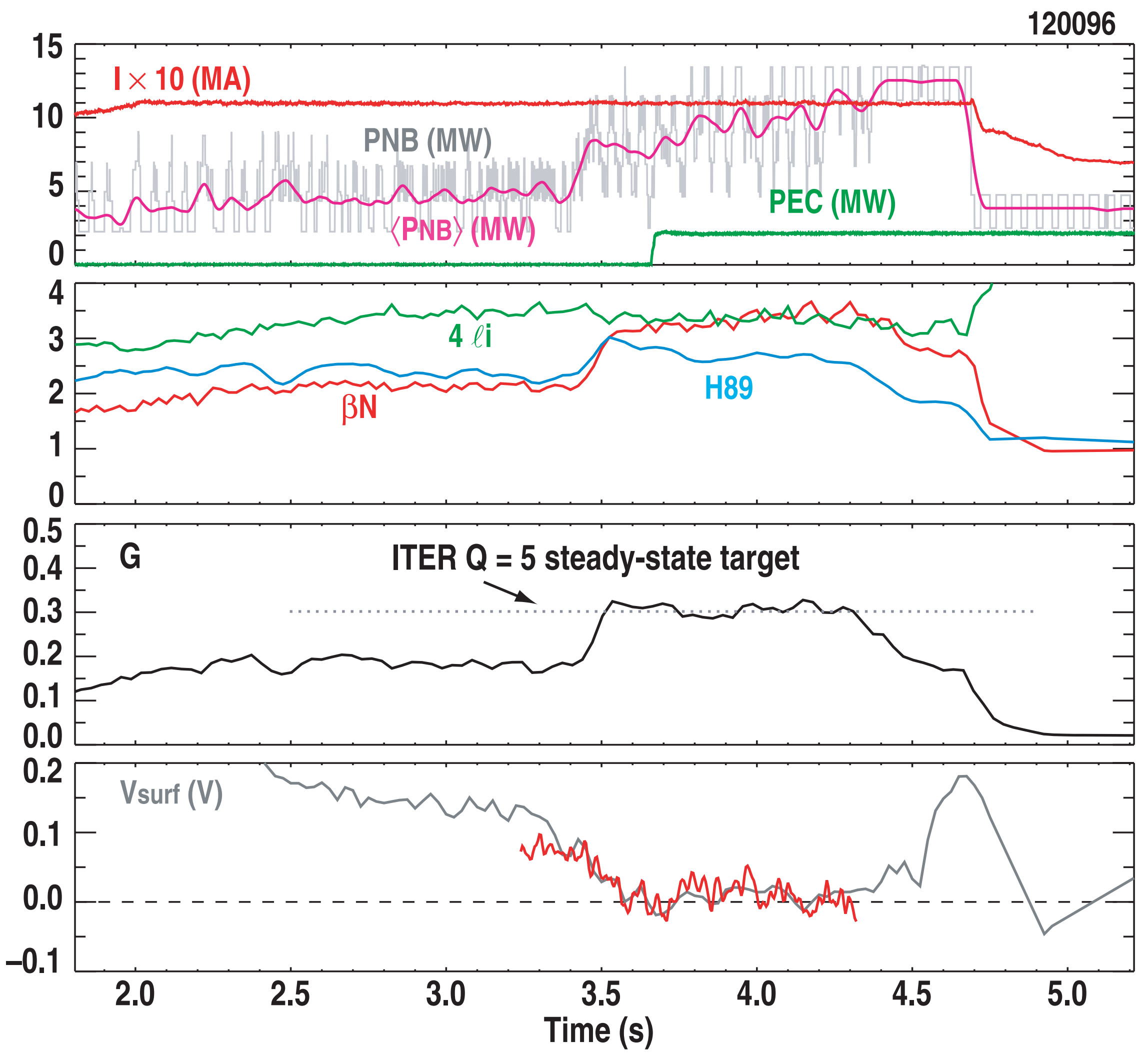
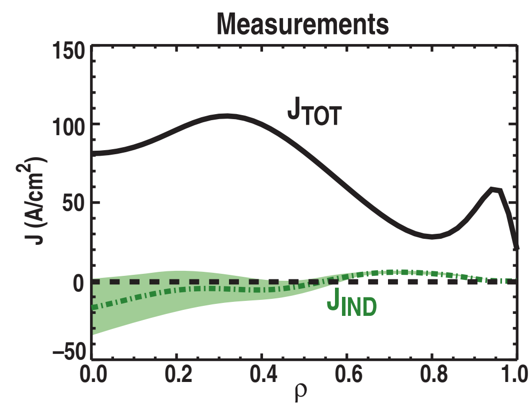
EXISTENCE PROOF OF HIGH q_{min} STEADY-STATE SCENARIO HAS BEEN OBTAINED ON THE TRANSPORT TIME SCALE



- Pressure at or above the no-wall pressure limit ($\beta_N \geq 4\ \ell_i$) for high fusion power
- Elevated q_{min} (>1.5) for enhanced bootstrap current (f_{BS} ~ 0.6)
- Reduced current (q_{95} ~ 5) to minimize noninductive current requirements



• Also established on JT-60U

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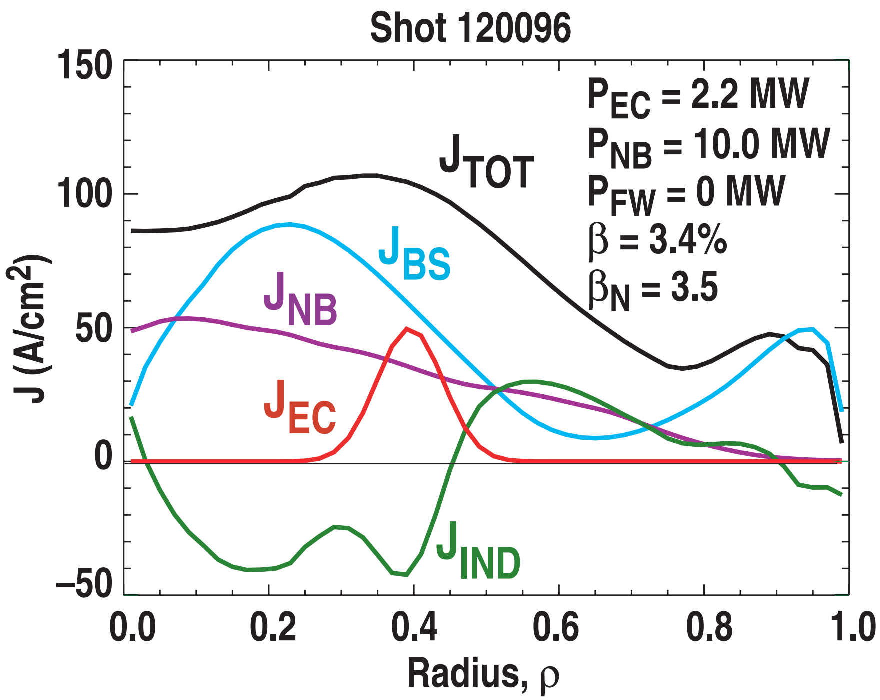
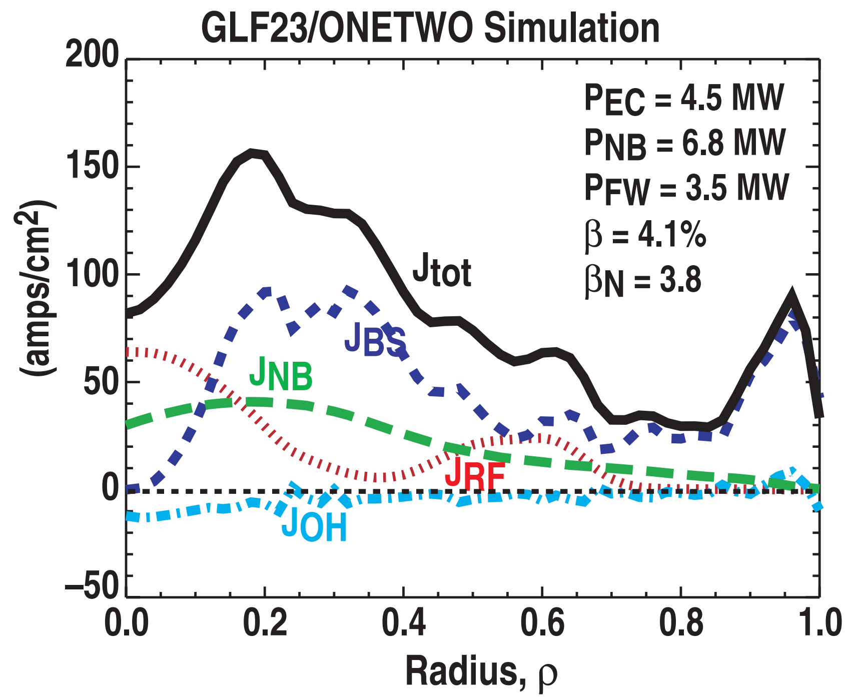
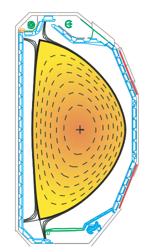
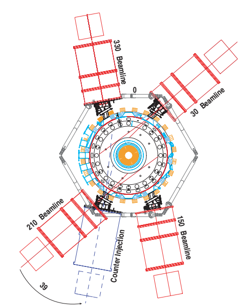
SIMULATIONS BENCHMARKED BY PRESENT EXPERIMENT INDICATE STEADY-STATE OPERATION FOR >5 s SHOULD BE POSSIBLE





- Simulations indicate additional ECCD and FWCD with less NBCD should lead to better current profile alignment
- Simulation consistent with planned upgrades
- Improved J(ρ) measurement with new MSE system will facilitate optimization





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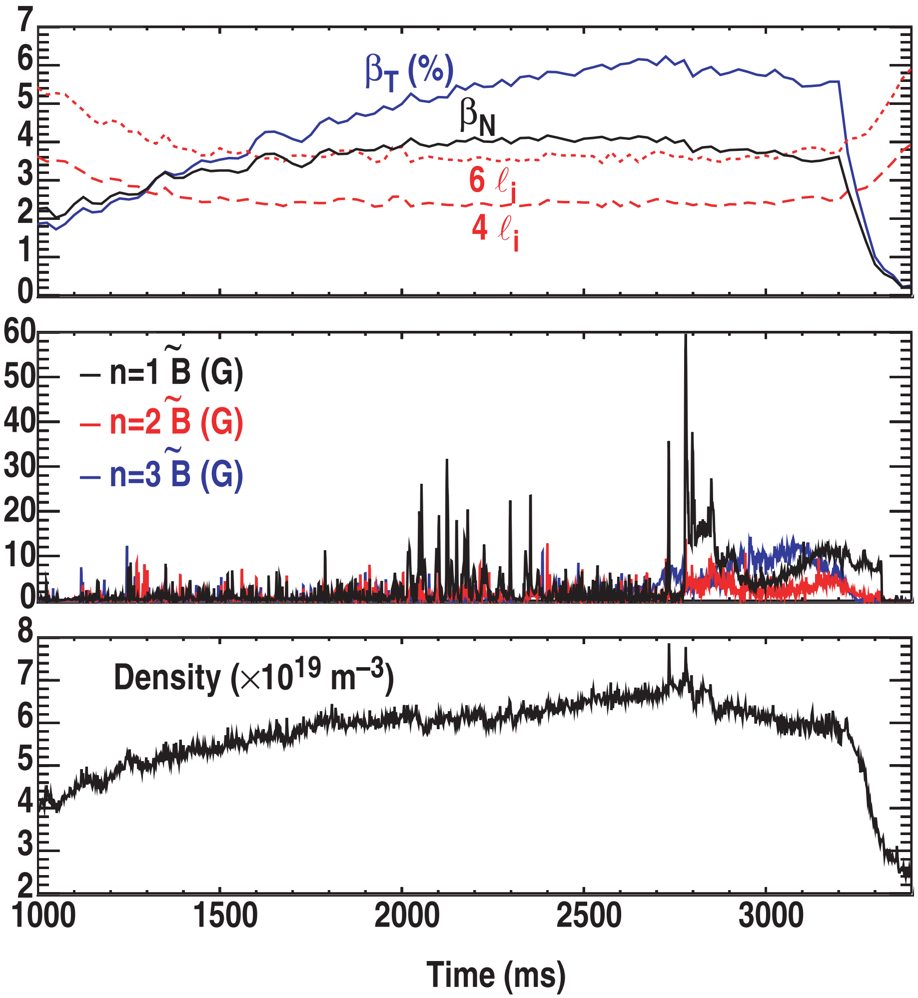
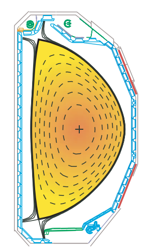
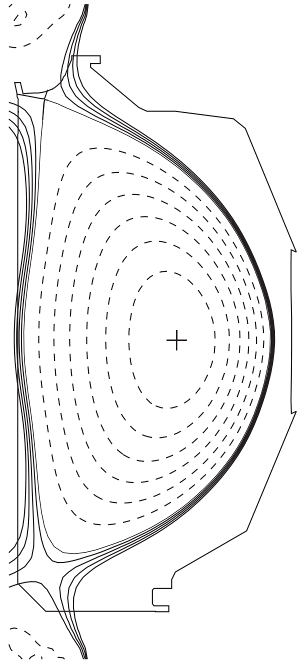
RWM STABILIZATION ALLOWS SUSTAINED OPERATION AT β_N VALUES NECESSARY FOR FULLY NON-INDUCTIVE OPERATION ($\beta_N >> \beta_N^{no\text{-}wall}$)



- C-coil and I-coil used for simultaneous feedback control of error fields and RWM
- $\beta_N \approx 4$, $\beta_T > 6\%$ with $q_{min} > 2$
- High δ shape
  - Good for stability
  - Not for n_e control





  - New divertor will allow better density control in high δ divertor

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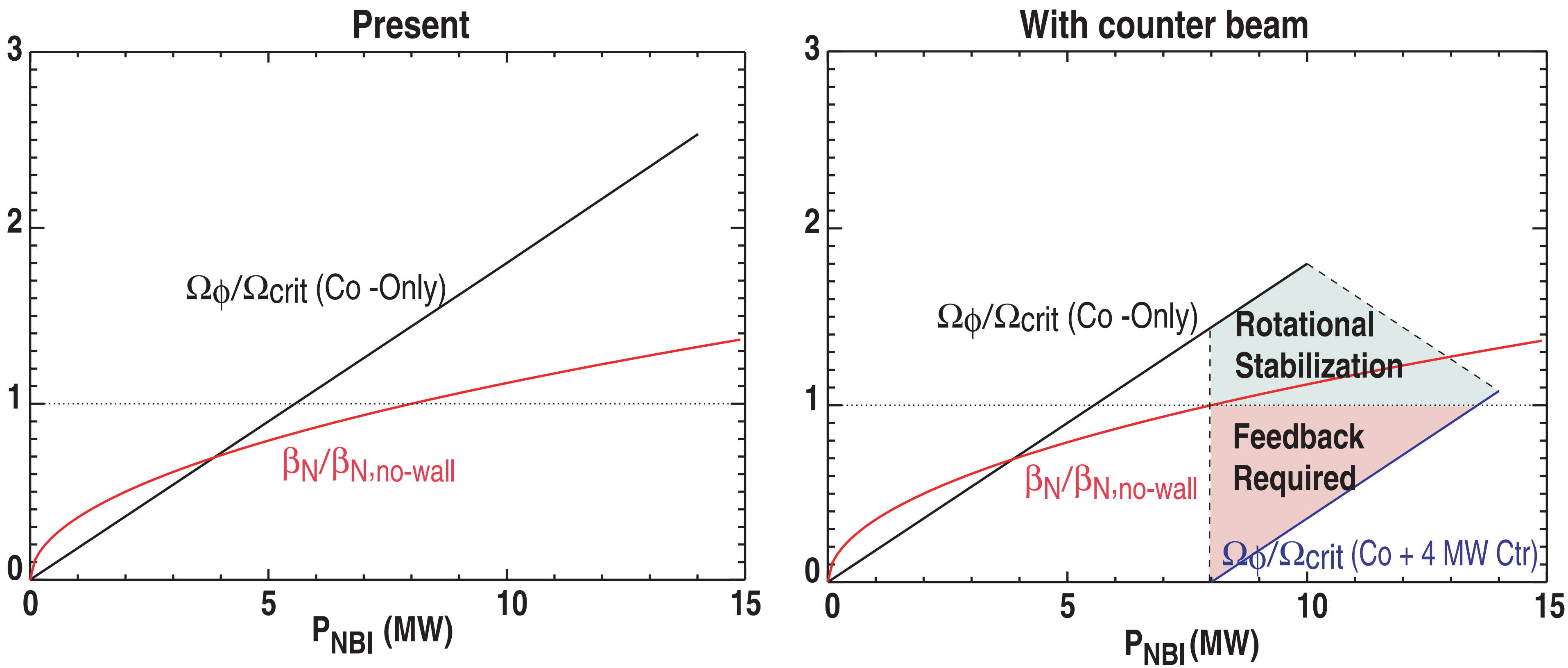
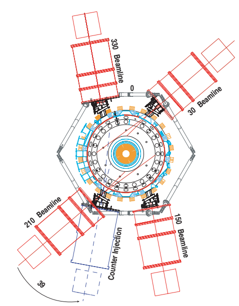
COUNTER BEAMLINE WILL ALLOW EXPLORATION OF HIGH β REGIMES AT BOTH LOW AND HIGH ROTATION



- Test theories of RWM stabilization and dissipation with $0 \le \Omega_\phi/\Omega_{crit} \le 1.5$
- Allows test of RWM feedback control under realistic reactor conditions
- Advanced tokamak can proceed independent of RWM feedback work



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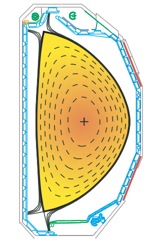
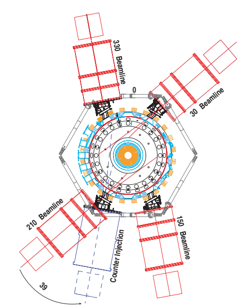
NEAR-TERM ADVANCED TOKAMAK PROGRAM WILL FOCUS ON IMPROVING CURRENT PROFILE ALIGNMENT AND DEVELOPING PROFILE CONTROL TOOLS

- Improved current profile alignment
  - Increased shaping for higher β_N
  - Improved density control for higher current drive efficiency



- Current profile control
  - Develop tools and algorithms for controlling J(p)

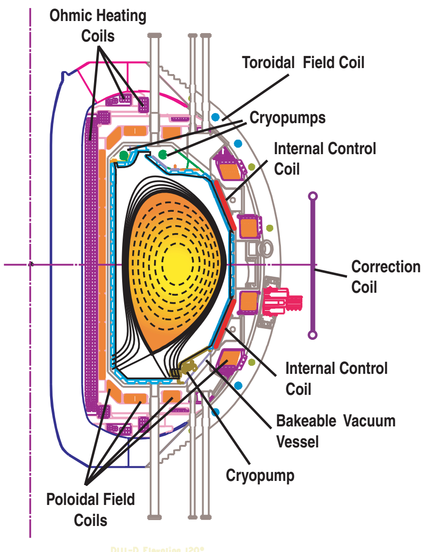
- Pressure profile control
  - Evaluate methods for broadening the pressure profile
- RWM stabilization
  - Continue to improve feedback algorithms for both rotationally stabilized and low rotation targets



- Integration and optimization

DIII–D IS UNIQUELY POSITIONED TO ADVANCE THE SCIENCE OF FUSION ENERGY AS WE PREPARE FOR ITER AND BEYOND

Machine Versatility



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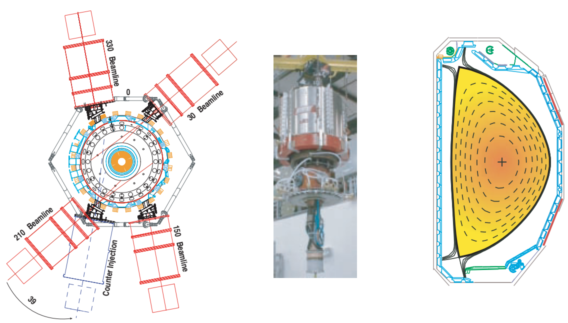
State-of-the-Art Tools



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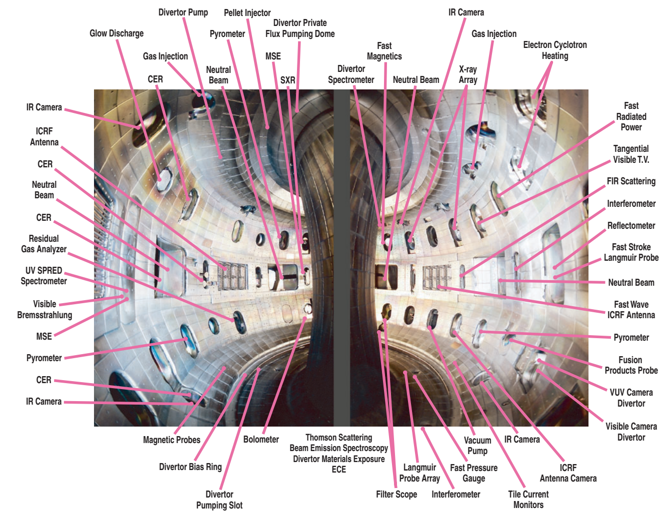
Comprehensive Diagnostics



International Research Team

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A unique opportunity to make significant advances towards:

- A predictive understanding of fusion plasmas
- Success of ITER in its baseline mission
- An enriched ITER research program
- Realizing the potential of steady-state tokamak operation

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